

New debris disk candidates: 24 μ m stellar excesses at 100 Myr

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ABSTRACT

Sixty three members of the 100 Myr old open cluster M47 (NGC 2422) have been detected at 24 μ m with *Spitzer*. The Be star V 378 Pup shows an excess both in the near-infrared and at 24 μ m ($K - [24] = 2.4$ mag), probably due to free-free emission from the gaseous envelope. Seven other early-type stars show smaller excesses, $K - [24] = 0.6 - 0.9$.

Among late-type stars, two show large excesses: P922 – a K1V star with $K - [24] = 1.08 \pm 0.11$ and P1121 – an F9V star with $K - [24] = 3.72 \pm 0.02$. P1121 is the first known main-sequence star showing an excess comparable to that of β Pic, which may indicate the presence of an exceptionally massive debris disk. It is possible that a major planetesimal collision has occurred in this system, consistent with the few hundred Myr time scales estimated for the clearing of the Solar System.

Subject headings: infrared: stars — planetary systems: protoplanetary disks — open clusters and associations: individual: M47

1. Introduction

A knowledge of circumstellar disk evolution is crucial to understanding the planet formation process. The current paradigm predicts that optically thick accretion disks left over

from star formation should dissipate as material is accreted, photoevaporated, or driven out of the system, leaving a remnant or debris disk formed by collisions between large bodies in a nascent planetary system (Hollenbach, Yorke, & Johnstone 2000; Wyatt & Dent 2002). Studies of how these circumstellar debris disks evolve in the planet-forming zone from 1 to 10 AU, where the disk emission emerges in the mid- and far-infrared, have been limited by the sensitivity of the previous space-based infrared missions, IRAS and ISO. The small number of F and A stars within their reach has undermined attempts to determine the frequency of excess emission. Claims of decreasing amounts of excess emission with age (Spangler et al. 2001) or an upper limit to the age of stars with debris disks (Habing et al. 2001) have been disputed by others who question the S/N of the excesses in question and/or the reliability of age estimates for nearby field stars (Decin et al. 2003).

The solution to this problem is to survey for debris disks around stars in young clusters of reliable and disparate ages. The high sensitivity of the *Spitzer* MIPS instrument at last puts this goal within reach for nearby young clusters. The use of M47, a young Galactic open cluster, as a calibration target during the *Spitzer* in-orbit checkout has provided an early opportunity to perform such a survey.

Messier 47 (NGC 2422) is a reasonably compact (core radius 30 arcmin, Barbera et al. (2002)) cluster of several hundred stars (Ishmukhamedov 1967; Mermilliod 1986; Prisinzano et al. 2003) at galactic latitude 3° and distance around 450pc (see discussion in Sec 3). Its age of 80 ± 20 Myr (Rojo Arellano, Pena, & Gonzalez 1997; van Rensbergen 1987), is approximately the same as that of the Pleiades. Stromgren photometry of M47 indicates that its metallicity is also similar to that of the Pleiades and α Per clusters (Nissen 1988). Despite its proximity to the galactic plane, M47 has a small measured reddening of $E(B - V) = 0.05 - 0.07$ (Shobbrook 1984; Nissen 1988).

2. New Observations

2.1. Spitzer Measurements

A region around M47 was observed with MIPS (Rieke et al. 2004) as a verification of the scan map parameters during the in-orbit checkout period (ads/sa.spitzer#0007427328). The sky coverage is non-uniform: the effective exposure time varies over the combined $20' \times 60'$ map, from a minimum of 100 seconds at the edges to a maximum of about 600 seconds in the central $\sim 5' \times 60'$ strip. The data were reduced using the instrument team Data Analysis Tool (Gordon et al. 2004). The $24\mu\text{m}$ mosaic is shown in Fig. 1. It is oversampled by a factor of two, i.e., the pixel size is $1.27''$. The sky coverage was not optimized for the $70\mu\text{m}$ array,

and only a few (possibly extragalactic) sources were detected at this wavelength. Thus, all our analysis has focused on the $24\mu\text{m}$ data.

Aperture photometry was performed using the DAOPHOT package (Stetson 1987). The signal aperture radius and inner and outer sky radii were set at 3.5, 9 and 18 pixels ($4.5''$, $11.5''$, and $23''$), respectively. A 0.73 mag aperture correction was applied to the measured values after examining the trend of the signal with aperture size on well isolated stars and in synthetic images. Final magnitudes were put on a scale where zero magnitude at $24\mu\text{m}$ is at 7.3 Jy. A total of 1093 objects was detected with $[24] < 12.0$ (0.12mJy) and $S/N > 5$.

2.2. Optical Spectroscopy

For the three possible M47 members with largest $K - [24]$ excesses (P1121, P369 and P922, Sec 4.2), optical spectra were obtained for us by J. Liebert in February 2004 using the blue channel of the 6.5-m Multiple Mirror Telescope spectrograph. With the $1''$ slit, the resolution was 3.6 \AA and the wavelength coverage was $3640 - 6790 \text{ \AA}$. Exposure times were 4, 4 and 5 min for P1121 ($V=12.7$), P922 ($V=14.5$) and P369 ($V=16.2$) respectively, at airmass 1.8.

3. Cluster Membership and Spitzer Detections

To interpret our results, we need to determine which $24\mu\text{m}$ sources are members of the cluster. Our first test for membership is the color-magnitude diagram. To construct such a diagram, we need to determine the cluster distance. A distance of $497^{+135}_{-88} \text{ pc}$ is indicated by four B stars with Hipparcos parallaxes (Robichon et al. 1999). Prisinzano et al. (2003) showed that the V vs. $V - I$ diagram is consistent with this distance and an age of 100 Myr. Estimates from Stromgren photometry include: Shobbrook (1984): $400 \pm 10 \text{ pc}$ (28 B-A stars); Nissen (1988): 425 pc (11 F stars); Rojo Arellano et al. (1997): $470 \pm 5 \text{ pc}$ (average) and $400 \pm 100 \text{ pc}$ (median) (36 B-F stars). We adopt a distance of 450 pc and $E(B - V) = 0.07$. Because the Prisinzano et al. list of cluster members is incomplete above $3.5M_{\odot}$, we added 11 bright stars near the cluster turn-off, taken from Robichon et al. (1999) and Rojo Arellano et al. (1997). Our photometrically selected sample of M47 members detected at $24\mu\text{m}$ then consists of 66 objects (Fig. 1).

We confirmed probable membership for 63 of these 66 stars by proper motion analysis. The UCAC2 (Zachari et al. 2003), ACT (Urban et al. 1997), ACC (Kharchenko 2001),

and Tycho (Hog et al. 2000) catalogs provided data for all the possible cluster members except P369 (which is relatively faint). Only P1218 is ruled out as a probable member, but P1078 has large errors in its proper motion and its status is unclear. All the remaining stars have appropriate proper motions for cluster membership: $\langle \mu_\alpha \cos \delta \rangle = -7.5 \pm 3.4$ mas/yr, $\langle \mu_\delta \rangle = 1.9 \pm 2.3$ mas/yr.

We detected at $24\mu\text{m}$ all M47 members lying within the boundaries of our mosaic and brighter than $V = 12$ mag (Spectral Type $\sim \text{F5}$, $1.5M_\odot$) and a few as late as $\sim \text{K}$. Accurate astrometry for the cluster members is available both from Prisinzano et al. (2003), who quote errors of $0.24''$, and 2MASS, with typical errors $< 0.1''$. At $24\mu\text{m}$, *Spitzer* positions are accurate to $\sim 1''$, but the dominant term is an offset in the scan direction that remains fixed for a campaign. If we take this offset out, the positional agreement between cluster members and $24\mu\text{m}$ counterparts is better than $0.5''$. The total probability of even one chance coincidence between random $24\mu\text{m}$ source and any cluster member whose photospheric flux is above our detection limit (0.12mJy) is about $P = \frac{\pi(0.5'')^2}{20' \times 60' \times (60'')^2} \times 1093 \times 63 = 1.3\%$. For objects brighter than 1mJy at $24\mu\text{m}$, the probability of such a coincidence is $< 0.25\%$ (take 195 instead of 1093). Thus, it is unlikely that there are any chance identifications for the brighter sources. Fig. 2 shows $J - H$ vs. $K - [24]$ for these stars.

4. Discussion

The histogram of $K - [24]$ colors for the majority of M47 stars can be described by a Gaussian centered at $K - [24] = 0.11$ mag and with FWHM 0.26 mag ($\sigma = 0.11$ mag). At these long wavelengths, for pure photospheric emission one expects $K - [24] = 0$ virtually independent of spectral type. Our distribution is shifted by $+0.11$ mag relative to this value; however, the offset is within the systematic error of our photometry (~ 0.10 mag, arising from uncertainties in absolute calibration (up to 10%) and in the aperture correction), and the scatter is of the order of the random error of our photometry ($0.03\text{--}0.08$ mag). We therefore define excess stars as those lying redwards of $(K - [24])_{\text{excess}} = 0.11 + 3\sigma = 0.44$ mag. The majority of M47 stars (55 out of 66) have $24\mu\text{m}$ fluxes consistent with a pure photospheric origin or at most a small excess. The remaining stars form two groups: early-type stars with $0.6 < K - [24] < 2.5$ and three late-type stars with extreme excesses $K - [24] > 1$.

4.1. Early type stars

Table 1 lists parameters of 8 M47 hot stars with $24\mu\text{m}$ excess (out of 33 total having $J - H < 0.1$, which is characteristic of A-B stars). The most extreme one – V378 Pup (= HIP 36981) – is a blue straggler and emission-line star, the only star in our sample that also shows a NIR excess (Dougherty & Taylor 1994). The incidence of substantial $24\mu\text{m}$ excesses is large: 24% of the early-type stars have excesses > 0.4 magnitudes. All of these stars are brighter than 1mJy, so the possibility of a chance coincidence with another source is very small.

It has been known since IRAS (Waters, Côté, & Aumann (1987), Cohen et al. (1987)) that the fraction of stars with infrared excesses in the field is the highest among B and M stars. This result is consistent with the high incidence of excesses among the early-type stars in M47. In the case of emission-line stars, the excess is explained by free-free processes in the extended gaseous envelopes/disks (Chokshi & Cohen 1987; Yudin 2001). The nature of the excess in non-emission-line stars is not well established: dust condensed after mass-loss episodes, dust from interstellar cirrus, and dust from circumstellar disks may all contribute (Kalas et al. 2002).

The Pleiades provide a natural comparison with M47. We identified probable Pleiades members by searching for stars within 1.5 degrees of RA 03:47:00 and DEC +24:07:00 (2000) and with proper motions within 7mas/yr of 17.9, -43.2 mas/yr respectively in RA and DEC. We used the IRAS FSC and PSC to identify infrared excesses in these stars. Our preliminary analysis of Pleiades *Spitzer* data shows that all the possible excess stars we found in this manner are surrounded by 0.'5-1' extended halos that contaminate the IRAS measurements. Since the surface brightness from the cirrus between M47 stars is an order of magnitude less than in the Pleiades, we doubt that such halos exist around M47 stars. In addition, at the distance of M47 such halos would be resolved by the MIPS 6'' beam – contrary to our observations (see Fig. 1). This shows the importance of M47 as a 100 Myr benchmark in disk evolution, since interpretation of Pleiades FIR data may be severely complicated by cirrus emission.

4.2. Late type stars

As one moves to later spectral types, the Vega phenomenon becomes very rare at wavelengths of $25\mu\text{m}$ and shorter. For example, Oudmaijer et al. (1992) list 462 stars with possible excesses in the IRAS catalog. If we take dwarf stars later than F3 and earlier than K7, brighter than $V = 8$, and at absolute Galactic latitude $> 10^\circ$ (to avoid confusion with

Galactic emission), then there are no stars with candidate excesses greater than 1.5 magnitudes at $25\mu\text{m}$. Mannings & Barlow (1998) report a similar study, with similar results. These studies searched to the full depth of the SAO star catalog, making chance associations a possibility. As a more stringent test, we took a complete sample of F and G dwarfs selected to have V magnitudes that would predict photospheric fluxes of 0.5 Jy or brighter at $25\mu\text{m}$ (and thus likely to be measured well by IRAS). This limit was set at $V = 4$ for F0 to F4, $V = 4.5$ for F5 to F8, and $V = 5$ for F9 to G8. For these stars, we searched the IRAS PSC for high quality measurements, and if no detection was reported there, checked if the star was listed in the FSC. Of a total of 59 stars with good IRAS measurements, none had an excess greater than 0.3 magnitudes in [12] - [25]. Similarly, Backman & Paresce (1993) found only two F or G dwarfs in the Bright Star Catalog (which goes to $V \sim 6.5$) with moderate (~ 0.5 mag) $25\mu\text{m}$ excesses (HR 506 and HR 818), and most recently, Laureijs et al. (2002) found one K dwarf (HD191408) with excess of 0.5 mag in their 25pc volume limited survey.

Therefore our discovery of three late type M47 stars with excesses $K - [24] = 1 - 4$ mag – P1121, P922, P369 – is very surprising. To clarify their nature, we obtained the optical spectra of these stars shown in Fig. 3. We used spectral standards from the NStars database¹ to classify our spectra. P369 turned out to be a reddened ($A_V \approx 1.0$ mag) K0 III-IV slightly metal poor star, with radial velocity $\sim +100$ km/s. It is also the only member candidate without a confirming proper motion measurement. Thus, we believe it is a background giant. On the other hand, P922 and P1121 have radial velocities consistent with cluster membership. Their spectral types are K1.5 V and F9 IV-V respectively, as expected from their positions on the cluster color-magnitude diagram. Both show signs of moderate chromospheric activity in CaII K and H lines (level "k" on scale of Gray et al. (2003)), which is a bit higher than observed in 800 Myr old Hyades stars (R. O. Gray 2004, private communication). No emission is seen in $H\alpha$ but slight infilling is present in $H\beta$ for P1121. In conclusion, P922 and P1121 have spectral signatures of young main sequence stars consistent with being M47 members (in addition to their proper motions and photometric characteristics).

P922 is close to the $24\mu\text{m}$ detection limit and its photosphere would be below that limit, so the probability of a chance coincidence of an unrelated source with some cluster member to produce a similar "system" is $\sim 8\%$. Although P922 is only slightly below the photospheric detection limit, in this calculation we have included all known cluster members within the *Spitzer* image (~ 380). Therefore, a chance coincidence is possible but not highly likely. P922 possesses an excess at $24\mu\text{m}$ similar to the extreme debris disk stars such as ζ

¹<http://stellar.phys.appstate.edu>

Lep (A2 Vann, 370 Myr).

P1121 is an exceptionally interesting object. All the indicators (photometry, spectral type, proper motion, radial velocity) place it within the cluster. Its image (Fig.1) is point-like with no indication of extended emission in its vicinity. It is 7mJy at $24\mu\text{m}$ and it is above our photospheric detection limit, so the probability of any chance association of a source this bright (25 out of 1093 total) with a cluster member is only $\sim 0.03\%$. If it is bright at longer wavelengths, it might have a disk as massive as seen in β Pic ! It is also possible that it is surrounded by a less-massive disk lying much closer to the star than is typical. At the age of P1121, Poynting-Robertson drag should have cleared out most of a thick, primordial disk. It is more likely the disk has been renewed by planetesimal collisions. This possibility is particularly interesting given the arguments that the solar system went through a phase of disk clearing, planet building, and violent planetesimal collisions for its first few hundred Myr (Hartmann et al. 2000).

5. Conclusions

We find substantial infrared excesses at $24\mu\text{m}$ in 10 stars that are members of the 100 Myr old cluster M47. The most interesting example is P1121, which is of spectral type F9 IV-V, yet has $K - [24] \sim 3.7$. If this excess is due to a debris disk, it likely has a large mass and is a very rare object judging from IRAS and ISO observations of the debris-disk phenomenon.

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Table 1. $24\mu\text{m}$ excess stars in M47

P.N	Name	SpT	M_V	J-H	K-[24]	F_{24} (mJy)
...	HIP 36981	B2-B5 Ven	-2.61	0.02	2.42	558.89 ± 0.51
...	HIP 36967	B5-B9 Vn	-0.33	-0.05	0.71	8.86 ± 0.05
...	HD 60995	B8-B9 V	0.38	-0.03	0.72	5.19 ± 0.05
1152	2MASS 07371449-1425179	...	1.73	0.00	0.62	1.58 ± 0.03
1155	BD -1402028	A2p	2.07	0.01	0.92	1.67 ± 0.02
1173	2MASS 07362205-1430283	...	2.13	-0.00	0.86	1.55 ± 0.02
1172	2MASS 07365524-1433176	...	2.42	0.05	0.68	1.13 ± 0.03
1182	2MASS 07370687-1431348	...	2.75	0.05	0.74	1.14 ± 0.03
1121	2MASS 07354269-1450422	F9 IV/V	4.40	0.28	3.72	7.31 ± 0.03
922	2MASS 07364576-1434348	K1 V	6.27	0.45	1.08	0.23 ± 0.02
369 ^a	2MASS 07372200-1424262	K0 III/IV	...	0.66	3.01	0.94 ± 0.03

^aOur spectrum indicates it is not a cluster member.

Note. — P.N – numbering sequence from Table 4 of Prisinzano et al. (2003); SpT – from the literature (VizieR; Mermilliod 2004; Hartoog 1976; Dworetzky 1975), except for late types (this work); M_V – assuming distance 450pc

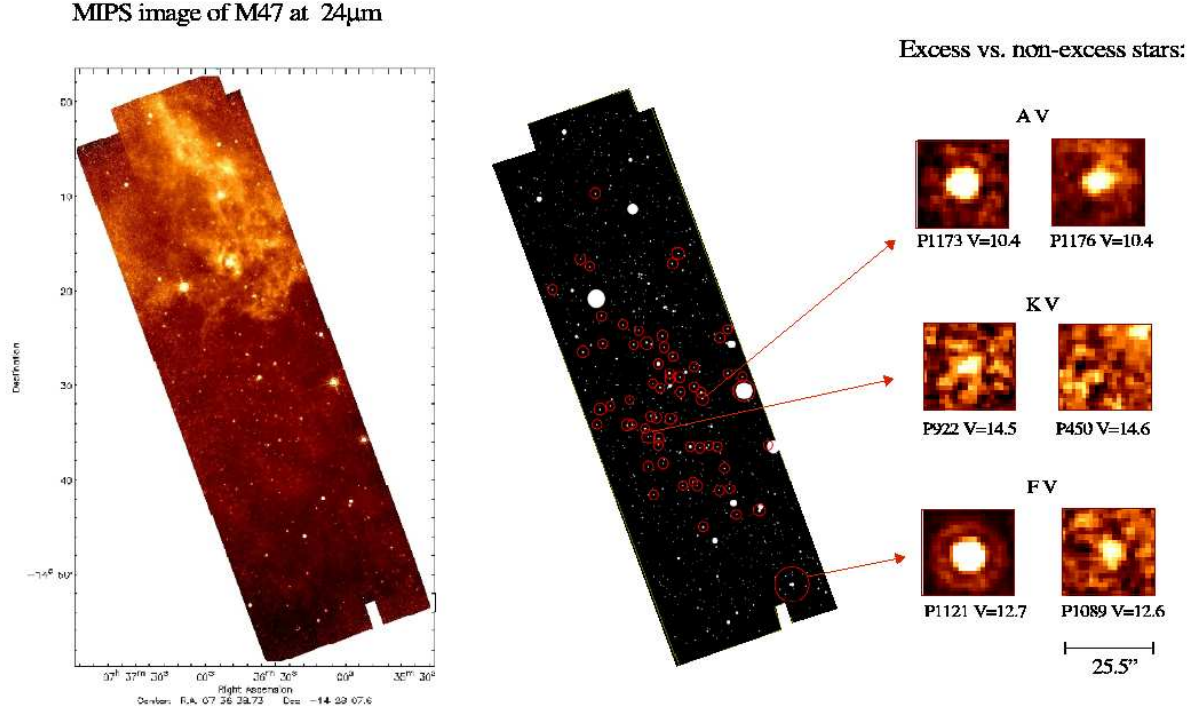


Fig. 1.— Left panel – M47 mosaic. Central panel – sources detected at $24\mu\text{m}$, red circles represent $24\mu\text{m}$ excess in M47 members (size $\sim K - [24]$). Right panel – magnified images of some excess stars (left column, arrows pointing to the position on the map), compared to similar magnitude V , $B - V$ non-excess stars (right column).

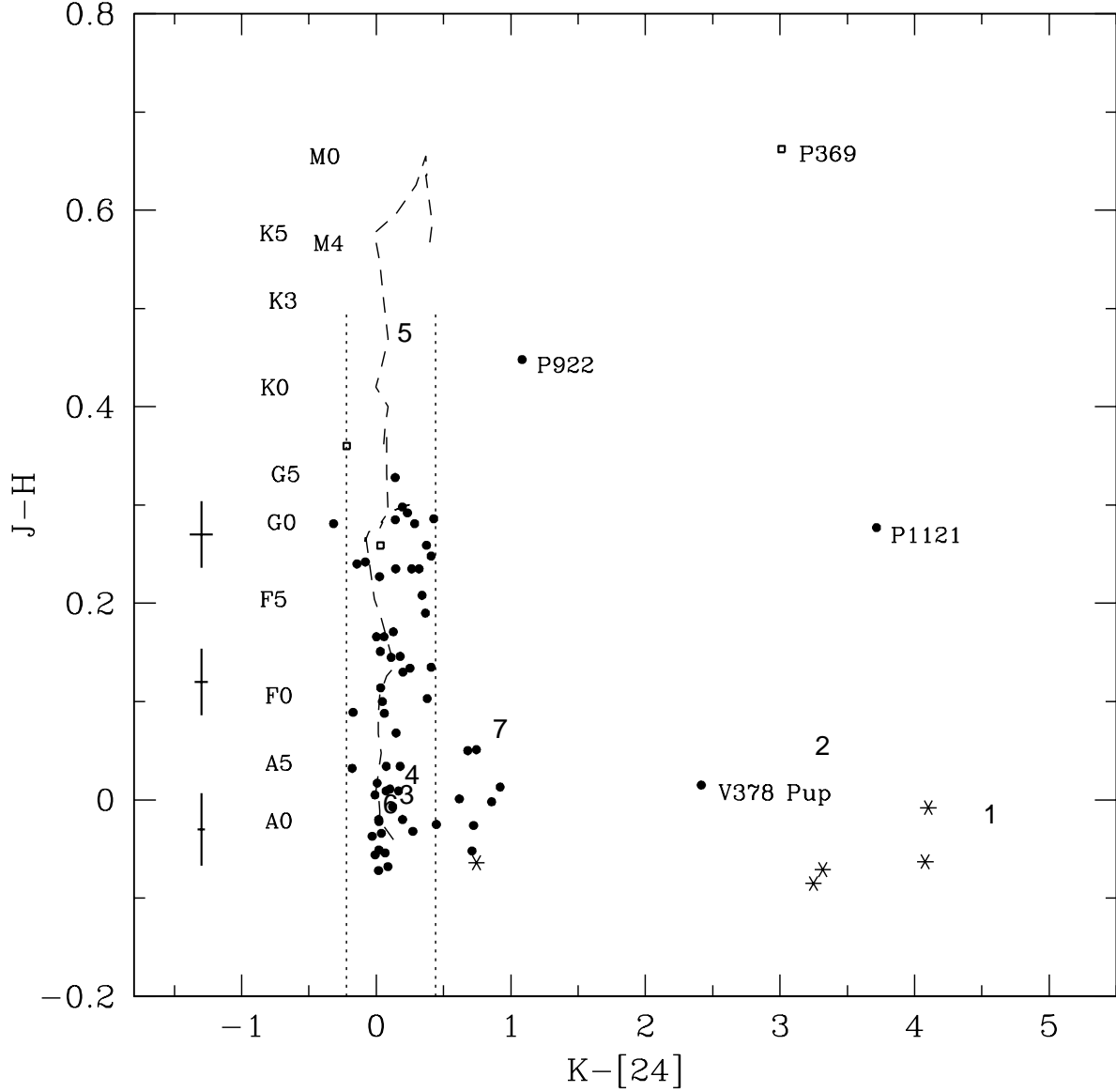


Fig. 2.— IR color-color diagram of M47 in comparison with Pleiades and field debris disk stars. Solid circles: M47 members; squares: membership uncertain due to lack of proper motion information; asterisks: Pleiades stars detected by IRAS; 1: HR 4796A (A0V 10Myr), 2: β Pic (A3V 12Myr), 3: Fomalhaut (A3V 220Myr), 4: β Leo (A3V 240Myr), 5: ϵ Eri (K2V 330Myr), 6: Vega (A0V 350Myr), 7: ζ Lep (A2nn 370Myr). Dashed line: locus of main sequence stars converted from $K-[12]$ colors in Kenyon & Hartmann (1995) by assuming $[24] = [12] + 0.08$, where 0.08 arises because of IRAS color corrections. Dotted lines: adopted 3σ boundaries on non-excess stars. The crosses on the left represent typical errorbars on M47 photometry as a function of $J-H$ (, or brightness for MS stars). Sources of photometry: JHK – 2MASS and Ducati (2002), $[24]$ – MIPS for M47 and IRAS [25] for the rest stars.

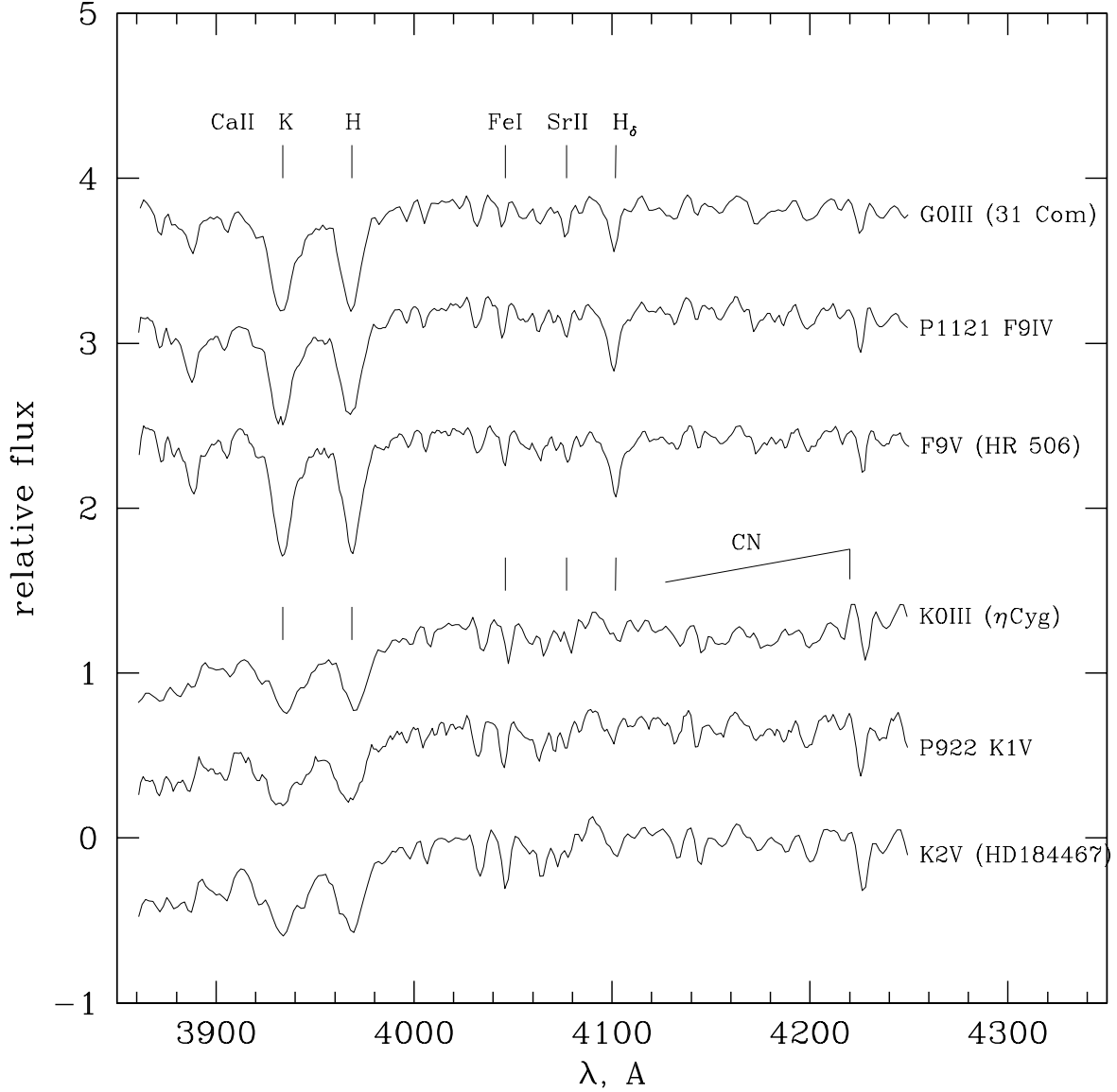


Fig. 3.— Portions of MMT spectra of P1121 and P922 in comparison with spectral standards (taken from NStars database). Sr II, as well as CN depression, is stronger compared to the neighbouring Fe I line in giants and weaker in dwarfs. Weak emission in the cores of Ca II lines is seen in P1121 and P922 confirming a young age for these stars.